Can the Horowitz-Maldacena Proposal be an Alternate to the Firewall?

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Recently, there have been discussions that black hole complementarity is inconsistent and that the firewall is required to prohibit the observation of duplicated information. It is thought that if the Horowitz-Maldacena proposal works as a selection principle, then this may be an alternative to the firewall. In this paper, we first point out that the Horowitz-Maldacena proposal seems to help black hole complementarity for charged black holes. However, if we consider the Hayden-Preskill argument further, which states that a black hole can function as an information mirror after the information retention time, then we can show that the Horowitz-Maldacena proposal cannot help black hole complementarity. This can be extended to neutral black hole cases. Therefore, in conclusion, we find that dynamical black holes do not respect complementarity, even with the Horowitz-Maldacena proposal.

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I. INTRODUCTION

Many ideas for resolving the black hole information loss paradox have been suggested [1]. One of the most important proposals is known as the black hole complementarity principle, whereby asymptotic and free-falling observers see different things while known physical laws, especially unitarity, remain preserved [2]. However, quantum information that consists of black hole internal states to be observed by the free-falling observer seems to be copied to outgoing Hawking radiation directed towards the asymptotic observer. This duplication of quantum information violates the no quantum X-erasing theorem. The black hole complementarity principle argues that the viewpoints of the two observers are essentially complementary. This poses no problem (in terms of the above information duplication) because the observers can never communicate. It is known that, if we assume the statistical entropy to be equal to thermal entropy [3] while keeping the unitarity of quantum mechanics intact [4], then the black hole complementarity principle would be manifest [5] due to quantum information theoretic arguments [6].

However, one needs to further check the consistency of black hole complementarity; is it really impossible to observe the duplication of information? This impossibility was confirmed only for the specific case of a Schwarzschild black hole with limited assumptions [7]. However, the authors did argue that complementarity might not hold if local horizons become different from global horizons. Numerical calculations of charged black holes indicate a distance separation between the inner and the Cauchy horizons [8]. This intervening space allows for gedanken experiments that can probe whether or not information duplication is possible [9]. To work as a good counterexample, in Refs. [8,10], a large number of scalar fields was assumed. On the other hand, this assumption could be reduced to a reasonable number that could be justified in string theory [11,12]. Furthermore, recently, the inconsistency of black hole complementarity was observed by other authors, and the firewall was introduced to prevent duplication of information [13,14]. Fortunately, however, a loophole existed, for it had been suggested that dynamical black holes might violate black hole complementarity through duplication experiments only when no relation existed between the singularity and the outer horizon. If a special conspiracy between the singularity and the outer horizon could be im-
implemented via quantum teleportation, a dynamical black hole might rescue black hole complementarity. Here, the Horowitz-Maldacena proposal [15] could function as a selection principle by using the quantum teleportation [9]. Then, this could be an alternative of the firewall.

In this paper, we argue that this resolution is insufficient in terms of rescuing complementarity (i.e., we will re-consider a resolution of Ref. [9]). Because it is more useful to intuitively understand, in Sec. II, we summarize the duplication experiment for a charged black hole. In Sec. III, we suggest that the Horowitz-Maldacena proposal can partly rescue the principle of black hole complementarity. However, in Sec. IV, by consideration of the Hayden-Preskill argument [16], we show that we can construct a situation whereby the selection principle still allows for duplication experiments. In Sec. V, we generalize to a neutral black hole to reduce the assumption of a large number of scalar fields. In Sec. VI, we summarize our results. Thus, we have justification for our claim that dynamical charged/neutral black holes unambiguously violate black hole complementarity.

II. DUPLICATION EXPERIMENT IN A CHARGED BLACK HOLE

If we assume suppression of pair-creation, the causal structure of a dynamical charged black hole can be obtained by pasting from the mass inflation scenario [17] to the extreme black hole solution. In the mass inflation scenario, the outer apparent horizon grows along the space-like direction, and a space-like singularity exists due to mass inflation [18]. If no Hawking radiation exists, the inner horizon sits at an infinite advanced time \( v \to \infty \) [19, 20]. The mass function behaves as \( m(u, v) \sim \exp \kappa_i(u + v) \), where \( \kappa_i \) is the surface gravity of the inner horizon, and \( u \) and \( v \) are the retarded and the advanced time parameters for the double null coordinate [17]. Thus, the inner horizon becomes a curvature singularity. However, if we paste this scenario to the extreme black hole, the inner horizon must approach the outer horizon. Then, the most natural guess is that the inner horizon bends in a space-like direction and approaches the outer horizon; this expectation has been confirmed by the authors through numerical calculations [8, 21]. Notice that one can access any location in the integrated domain by using finite \( u \) and \( v \). This implies that no curvature singularity exists in the general relativistic sense. Of course, because the mass function diverges exponentially, some curvature functions diverge on a scale than the Planck scale. This is resolved by re-scaling the unit length (i.e., Planck length), and this re-scaling can be implemented by tuning the number of massless degrees of freedom [8]. Finally, if we assume a large number of massless degrees of freedom, we can get the semiclassically convincing causal structure of a dynamical charged black hole (Fig. 1).

One important point is that the transition region between the mass inflation scenario and the extreme black hole requires the end of the space-like singularity, thus inducing the Cauchy horizon. By definition, one do no calculation beyond the Cauchy horizon. However, we can conjecture that a time-like singularity exists inside the Cauchy horizon. In this causal structure, a duplication experiment between the Cauchy and the inner horizons is possible [8, 9]. Free-falling matter can send a signal along the outgoing direction (\( A \) in Fig. 1). This information can be observed outside the black hole after the information retention time (\( B \) in Fig. 1) thus allowing an observer access to information duplication. Note that, if we assume a large number of massless degrees of freedom, all processes occur in the semiclassical region.

III. HOROWITZ-MALDACENA PROPOSAL AS A SELECTION PRINCIPLE

If there is a special relation between the singularity and the outer horizon, and if the conspiracy prevents Hawking radiation (\( B \) in Fig. 1) from containing information related to the out-going information that did not touch a singularity (\( A \) in Fig. 1), black hole complementarity holds. Although the relation is space-like, if quantum teleportation can be realized in a black hole, a conspiracy can be implemented. The authors argue that, the Horowitz-Maldacena proposal [15] can be used exactly for this purpose.

The Horowitz-Maldacena proposal assumes that [15]